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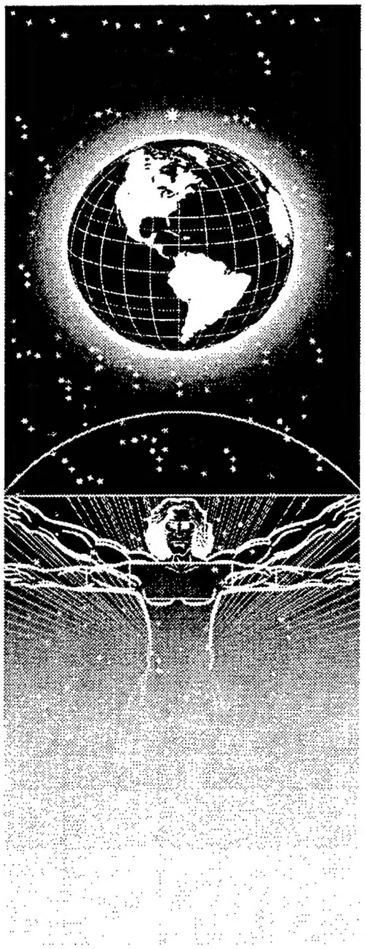

UNITED STATES AIR FORCE RESEARCH LABORATORY

Feasibility Study on Application of Fuel Cells as an Alternative Power Source for Flight Line Ground Support Equipment

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FOR THE COMMANDER

For [signature], Lt Col

JAY KIDNEY, Col, USAF, Chief
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This paper reports the results of a feasibility study to examine the operational and logistics feasibility of using Proton Exchange Membrane (PEM) Fuel Cells as an alternative power source for flight line aerospace ground equipment (AGE). The study compared a functionally equivalent fuel cell powered generator cart to the current configuration A/M32A-86D generator to determine if the fuel cell powered cart could compare favorably in the areas of power output, weight, size, reliability and maintainability, and life cycle cost. Several system design concepts were evaluated to determine which design concept best utilizes the fuel cell technology. The design concept presented is based on a variation of a modular DC bus architecture currently being developed by the U.S. Navy. Centralized reforming of hydrogen, hydrogen handling, and hydrogen safety issues are also presented as part of the design concept discussion.

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PREFACE

This report documents the results of a study to examine the feasibility of using Proton Exchange Membrane (PEM) Fuel Cells as a power source for flight line ground support equipment. The study was performed by SYTRONICS, Inc. and R-Net Engineering and Technology Ltd. for Armstrong Laboratory's Logistics Research Division. The study was funded under the Logistics Technology Research Support (LTRS) Contract F41624-97-D-5002, Delivery Order Number Five. Ms. Jill Ritter in AL/HRGO was the Armstrong Laboratory Task Manager.

SUMMARY

This paper documents the results of a study to examine the operational and logistics feasibility of using Proton Exchange Membrane (PEM) Fuel Cells as an alternative power source for flight line aerospace ground equipment (AGE). The study concluded that fuel cell powered AGE compared favorably against current internal combustion engine AGE relative to power, size, fuel usage, maintenance, supportability, life cycle cost, and overall ease of operation.

With the conclusion that fuel cells were a feasible power source for AGE, the study proceeded to examine various system design concepts that took advantage of the fuel cell's power characteristics and inherent modularity. The design concept presented in this paper revolves around a variation of a modular DC bus architecture already being developed by the U.S. Navy. Using this design concept, a fuel cell powered AGE unit can supply the typical flight line maintenance demands for electrical power, hydraulic, hand tool power, and air conditioning service. While this design concept is tailored for newer aircraft using DC internal power, the system can also support in service aircraft with the addition of devices incorporating the specific AGE function required.

The last major issue addressed in the study pertained to the fuel cell's hydrogen supply and associated safety issues. The study concluded that an off-cart or central processing facility to produce the hydrogen was more advantageous than the use of an on-cart fuel processor. The safety issues pertaining to hydrogen were not a large concern as anticipated. Maintenance personnel are already exposed to dangerous gases and existing procedures can be adopted to safely handle and use hydrogen.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

I. INTRODUCTION

The Armstrong Laboratory Logistics Research Division is dedicated to improving the supportability of Air Force systems and the productivity of maintenance personnel. The suitability of aerospace ground equipment (AGE) to meet the current demands of USAF missions directly affects both the supportability of Air Force systems and the productivity of maintenance personnel.

The current demands on the Air Force for high deployment rates with reduced manpower levels has caused the Air Force to examine all aspects of its operations to find improved ways to do business. AGE is a key element in both home base and deployed operations and is a major portion of the cargo load requirements for deployments. Also, the technology and concept of operation and maintenance of AGE has not changed for many years. Finally, there are increasing demands on the Air Force to greatly reduce or eliminate the environmentally hazardous emissions generated by the current AGE. Consequently, AL/HRG is working to find new technologies and methodologies to improve the suitability of AGE for current and future Air Force missions.

Proton Exchange Membrane (PEM) Fuel Cells are a potential source of power that will eliminate hazardous emissions from powered AGE. Fuel cells are also silent, operate at low temperatures, and are more fuel efficient than internal combustion engines. Fuel cell power for AGE may also reduce mobility loads, improve flight line operations, and provide reduced maintenance requirements. Consequently, fuel cells are potentially an outstanding power source for Aerospace Ground Equipment.

The purpose of this study was to consider the use of fuel cells as a power source for AGE. This study reviews the current and projected performance of fuel cells, reformers, and associated power generation components; compares fuel cell powered AGE with current AGE technology; and explores how fuel cell powered AGE could be used on the flight line and its resulting impact on maintenance and operations. Some advanced concepts for the design of fuel cell powered AGE are also offered. Fuel cell technology is not reviewed in this study, except as necessary to evaluate projected fuel cell performance and consider the impacts of using fuel cell powered AGE in a flight line environment.

II. BACKGROUND

The end of the Cold War and the large scale deployments planned for combat in that environment have given way to a world situation that requires numerous smaller, rapid reaction deployments throughout the world. In addition, the draw down in forces is reducing the amount of cargo space available for deployment and reducing the number of maintenance personnel available, both at home bases and for deployed locations. The combination of these factors is forcing the Air Force to improve the productivity of its maintenance operation and personnel. While new technologies and methods of doing business have been introduced in many areas, one area that has essentially remained unchanged for many years is flight line ground support equipment. The static nature of AGE has been exacerbated by the procurement of AGE under "sustaining" contracts. This procurement philosophy has limited the ability of both vendors and the Air Force to consider

introduction of new technologies into AGE. The Air Force has recognized this problem and is now preparing a Mission Need Statement (MNS), Aircraft Aerospace Ground Equipment (AGE) System 702-97, which will initiate a new acquisition for advanced AGE. The new MNS provides a window of opportunity to introduce new technologies that will improve AGE performance; promote more productive operation and maintenance concepts; and reduce manpower, training, personnel skill levels, and logistics support requirements.

A major problem plaguing current AGE is the demand by the public and by law for the Air Force to reduce the high level of environmentally hazardous emissions from the current reciprocating and turbine engines used in powered AGE. The Clean Air Act requires the Air Force to reduce Nitric Oxide (NOX) emissions from flight line equipment to 4g/brake-hp-hour or less. The goal of the Clean Air Act Project is to reduce the output of certain pollutants to zero and further reduce the emissions of hazardous air pollutants (HAP). Another problem associated with internal combustion engines is that they have very hot surfaces, produce hot asphyxiating exhausts, and are extremely noisy, all of which require procedures and protective devices for flight line personnel that interfere with maintenance activity and reduce communication on the flight line.

AL/HRG has conducted various studies and projects to address the many issues stated above. These include the Electric Multi-function Aerospace Ground Equipment (EMAGE) study [Ref 1], the Green AGE project, and Multi-function/Modular Aircraft Support System (MASS) program. In these efforts, particularly EMAGE, the use of fuel cells was identified as a potential power source for AGE. Fuel cells have also been identified as practical power sources in other applications. The U.S. Army, U.S. Navy, NASA, Department of Energy, and the major automobile manufacturers are developing fuel cell technology for use as a primary and secondary power source in their respective applications. Collectively, these organizations are spending millions of dollars on fuel cell R&D. This level of investment emphasizes the commitment being made to position fuel cells as a practical and cost effective power source for both military and commercial power applications.

A portion of the above mentioned studies have compared fuel cell power plants to current AGE power sources and have concluded that fuel cells are potentially a good power source for AGE. However, these studies assumed a one-for-one drop in replacement of current power plants and did not address in any detail the operational and logistical impacts of using fuel cells on the flight line. The application of fuel cell technology to flight line AGE offers a unique opportunity to explore how this new technology can revolutionize the concept of AGE and how to better utilize and employ AGE to meet mission requirements. However, despite all the many advantages fuel cell technology can potentially offer the AGE community, it must first and foremost be a technology that makes sense for the flight line environment.

III. STUDY ISSUES

The PEM Fuel Cell Powered (FCP) AGE feasibility study sought to answer three basic questions:

- How would a PEM FCP AGE unit compare to a current diesel or turbine powered AGE in size, weight, performance, and life cycle cost?
- Is fuel cell technology a viable AGE technology from an operational and logistical point of view?
- What are some FCP AGE system design and operation concepts that fully utilize the inherent features of fuel cell related technology?

The application of fuel cell power to flight line AGE offers many advantages to the AGE community. Fuel cells are fuel efficient, quiet, do not produce asphyxiating gases, are not hot to the touch, and are inherently modular. Despite these many apparent advantages of fuel cells, two basic issues stand out: can FCP AGE provide the required power within a comparable power-to-weight and power-to-size ratio of current AGE and does it make sense to use fuel cell technology in an operational flight line environment? These basic issues must first be resolved before one can truly exploit the merits of fuel cell technology in AGE applications.

IV. APPLICATION OF FUEL CELL POWER TO AGE

Power systems for AGE have always involved rotating internal combustion engines and rotating generators. The first step of the study was to analyze the feasibility of a change to a solid state, non-rotating power generation system using fuel cells. Fuel cells and their associated components were the technologies evaluated in this study.

Incorporating fuel cell power plants in flight line AGE can be accomplished using a number of approaches. Two approaches were considered in this study. The first approach assumed a straight replacement of several major components in a typical flight line ground generator cart. The benefit of this approach is that much of the overall design and employment concept remains the same thus providing a means to directly compare FCP generator technology to current generator technology in the desired areas of power output, physical dimensions, and operational & logistical compatibility. The purpose of this implementation approach was to provide confidence that fuel cell technology was feasible for use in a flight line environment. While this approach facilitates the comparative analysis, it does not allow the system designer nor Air Force operators to take advantage of the fuel cell's inherent attributes.

Once it was determined that fuel cell technology was a feasible power source for AGE, the study was expanded to look at FCP generator design concepts that could satisfy current aircraft AC and DC internal power requirements and also take advantage of the inherent benefits of fuel cell related technology. A comparison of on-cart and off-cart JP-8 reforming and incorporation of new technologies that would contribute to consideration of modular AGE systems are included as well.

Fuel Cell Powered Generator Components

Current AGE ground power carts consist of a reciprocating engine, either diesel or turbine, a rotating armature AC generator connected to the engine, electrical conditioning components, control panel and instruments, fuel tank, cart frame, and various cables. Most operational aircraft currently in service require 115 VAC, 3 phase, 400 Hz power with the AC power being supplied by a generator. Some aircraft, such as the F-22, require DC aircraft internal power. In this case, a separate AC-to-DC converter cart is used in conjunction with an A/M32A-86D generator to convert the generator AC output to the F-22's required 270 VDC power.

A fuel cell powered (FCP) generator would consist of the same components except that an AC generator is not required. A capacitance device may be required in the electrical conditioning package due to the fuel cell's slower response to power demands. The fuel cell's natural DC power output, coupled with newer aircraft requirements for DC internal power, would probably steer a FCP generator design towards a DC bus architecture. An inverter module would be added if there were a requirement to power older aircraft using 3 phase, 400 Hz AC aircraft internal power. Figure 1 shows a comparison between the components for an internal combustion engine powered generator and those for a fuel cell powered generator.

As illustrated in Figure 1, incorporating a fuel cell power plant into an AGE unit affects several major systems. The major systems effected include the power plant, power generation components, and the fuel system. A more in-depth discussion of these systems and their current level of technology and performance are discussed below.

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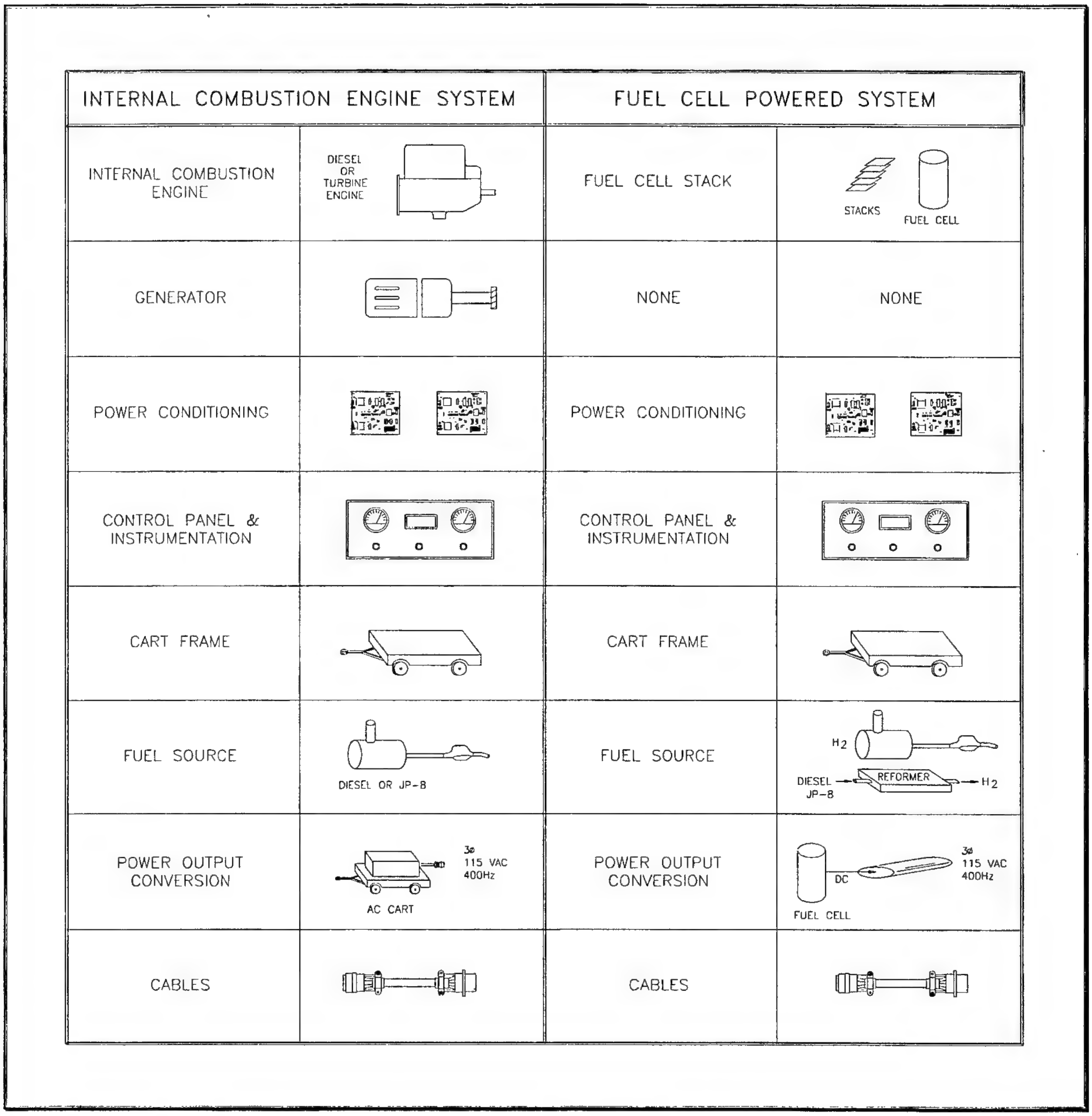


Figure 1. Components of Internal Combustion Engine and Fuel Cell Powered Generators

<u>Fuel Cells</u>

A fuel cell is a power source that generates electrical power through an electrochemical reaction. The reaction combines hydrogen (the fuel) and oxygen (from air) to form water and release electrons that can be gathered to produce a current. The fuel cell will continue to generate electrical power as long as hydrogen fuel is provided to the cell. The hydrogen fuel can be provided as a pure hydrogen gas or as the output of a hydrocarbon fuel processor. Since a fuel cell (like a battery) generates electricity directly from an electrochemical process without going through

a heat generation phase, a fuel cell power plant does not have the Carnot limitation inherent in an internal combustion engine and can be scaled to the desired size with only a small loss in efficiency.

The Proton Exchange Membrane (PEM) Fuel Cell was used as the power plant application in this study. A PEM Fuel Cell operates across a proton exchange membrane that acts as the electrolyte in the fuel cell. The proton exchange membrane is part of the Membrane Electronic Assembly (MEA), as illustrated at Figure 2, and separates the anode from the cathode. When hydrogen is present at the anode, protons migrate through the proton exchange membrane, leaving electrons at the anode. The protons combine with oxygen at the cathode (in the presence of a catalyst) forming water. The potential created between the anode and the cathode can be used as a direct current power source.

Fuel cell performance is primarily determined by the efficiency of the electrochemical process at the MEA and is measured in amperes per area of membrane at a given voltage (A/cm^2). While the voltage across a given cell is relatively fixed, the amount of current generated by the cell is dependent upon the surface area (cm^2) of the proton exchange membrane where the reaction occurs.

In order to have sufficient surface area of the proton exchange membrane in a reasonable package, individual fuel cells are aggregated into a "fuel cell stack" to become a workable, refuelable power source. The cells in a stack are normally connected in series to form a basic fuel cell stack. The stacks can be further connected in series or parallel to provide a power source with the needed power output and with the desired combination of voltage and current.

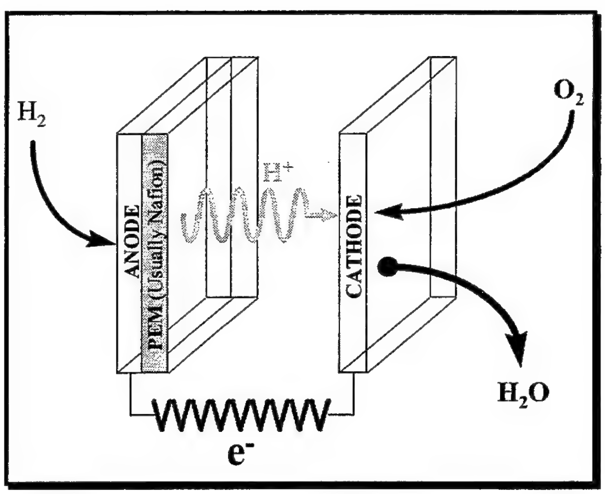


Figure 2. PEM Fuel Cell Membrane Electrode Assembly (MEA)

Fuel Cell Performance Measures: There are a number of considerations in determining the performance of a fuel cell power source, but the basic issue is what will be the size and weight of the power plant. Since a fuel cell stack can easily be scaled to the needed power requirement, fuel cell performance is expressed as a ratio of the power produced (watts) per volume or weight. The two basic fuel cell performance measures that address volume and weight are:

- Power Density – the power produced per unit of volume (watts/liter - w/l)
- Specific Power – the power produced per unit of weight (watts/kilogram - w/kg)

Efficiency of the MEA is the primary factor in fuel cell performance. However, a number of external factors have significant influence on the performance of a specific MEA, as evidenced by the fact that a survey of the fuel cell industry reveals that power density and specific power claims for various fuel cells using the same or very similar MEAs vary widely. These key factors are:

- Source of hydrogen fuel - pure hydrogen or output of a hydrocarbon fuel processor
- Source of oxygen - pure oxygen or air
- Catalyst Loading
- Operating Pressure

A detailed discussion of these key factors and their influence on fuel cell performance is presented in Appendix A.

Fuel Cell Performance: Fuel cell technology has made vast improvements over the years, but it is necessary to project fuel cell performance for the next several years in order to have a reasonable idea of what the performance would be if fuel cell powered AGE would be procured by the Air Force. Many of these developments are proprietary and are closely held by the developers.

However, much of the fuel cell development in the United States is being funded or overseen by the Department of Energy. In order to provide a credible base line estimate of fuel cell power plant performance that is standardized and useful, we have selected the fuel cell stack technical targets for a 40 kW fuel cell stack contained in the Department of Energy Automotive Technologies R&D Plan [Ref 2]. This estimate of fuel cell stack performance (see Table 1) is accepted by the industry and represents a conservative estimate of fuel cell performance. While the technical targets established by DOE are aggressive, the international need for high performance, low emissions power sources has resulted in hundreds of millions of dollars being spent world wide on fuel cell improvements. One of these efforts, the High Performance Ambient Pressure (HPAP) fuel cell technology is discussed in Appendix B.

Characteristic	Unit	Calendar Year			
		1997	2000	2004	2008
Net Stack System Power Density	W/l	300	350	500	500
Net Stack System Specific Power	W/kg	300	350	500	500
Stack System Efficiency @ 25% Peak Power	%	50	55	60	60
Stack System Efficiency @ Peak Power	%	40	44	48	48
Precious Metal Loading	g/peak kW	2.0	0.9	.02	.02
Cost (per net peak kW)	$/kW	200	100	35	35
Durability (<5% power degradation)	hours	>2000	>5000	>5000	>5000
Transient Performance (10-90% pwr)	sec	10	3	1	<1
Cold Start-up to maximum power from -40°C / from 20°C	min	15 2	5 1	2 0.5	2 0.5
Emissions		<Tier 1	<Tier II	<Tier II	<Tier II
CO Tolerance (steady state)	ppm	10	100	1000	2000
CO Tolerance (transient)	ppm	10	500	5000	10000

Table 1. Technical Targets: Fuel Cell Stack Systems
Running of Hydrogen-rich Fuel from Fuel-flexible Fuel Processor
40 kW Peak Power (continuous)
(Excludes Fuel Processing/Delivery System)
(Includes Fuel Cell Ancillaries: i.e., Heat, Water, Air Management Systems)

The DOE fuel cell technical targets are a compilation of data and information from the fuel cell industry. The figures presented are for automotive application of fuel cell stacks--an application and size that is comparable to that required for USAF ground power systems. Furthermore, the DOE data are for reformate fuel, the system is pressurized, and the amount of catalyst is stated. The table also contains other fuel cell performance parameters that are of value to this study and that would have been beyond the scope of the study to gather. These performance targets are considered reasonable and achievable by the DOE and by the fuel cell industry.

Hydrocarbon Reformer

One major component of an AGE fuel cell power system is the JP-8 fuel processor (reformer) that extracts hydrogen from JP-8, releasing a gaseous stream called "reformate" which is approximately 50% hydrogen. While there are various ways of accomplishing the fuel processing, the favored technology at this time is the Partial Oxidation (POX) Reactor. This reformer has a number of sections that vaporize the fuel, accomplishes the partial oxidation of the gaseous fuel,

removes the sulfur and carbon, and converts/oxidizes CO to CO_2. Heavy hydrocarbons, such as JP-8 are more difficult to reform than are lighter hydrocarbons, such as gasoline, although the process is generally the same. At least one company, Arthur D. Little, has fabricated a JP-8 reformer.

One of the objectives of this study was to determine if the reformer should be included on the FCP generator or be a separate off-cart device. If a reformer is included on the FCP generator, it would be fully integrated with the fuel cell stack and the total volume and weight of the system would be less than the total of the individual subsystems. However, the reformer power density and specific power estimates provide reasonable data for an initial evaluation of the size and weight of a reformer that could be added to a FCP generator. The DOE R&D document used for fuel cell stack performance estimates also includes performance estimates for reformers (see Table 2). The size and weight of a JP-8 reformer would be larger than the gasoline reformer used in the table below, but would be at least partially compensated for by the full integration of a reformer and a fuel cell, if the reformer was part of the AGE unit.

Characteristic	Unit	Calendar Year			
		1997	2000	2004	2008
Energy Efficiency	%	70	75	80	80
Power Density	W/l	400	600	750	750
Specific Power	W/kg	400	600	750	750
Cost	$/kW	50	30	10	10
Start-up to Full Power	min	<5	<2	<1	<1
Transient Response (0-90% Power)	sec	30	20	10	5
Emissions		Tier II	Tier II	Tier II	Tier II
Durability (time between catalyst replacement)	hours	1000	2000	5000	>5000
CO Content Steady State	ppm	200	10	10	10
CO Content Transient	ppm	5000	500	100	100
H_2S Content in Product Stream	ppm	0	0	0	0
NH_3 Content in Product Stream		<10	<10	<10	<10

Table 2. Technical Targets: Flexible Fuel Processors (Using Gasoline Fuel)
(Excludes Fuel Storage)
(Includes Controls, Shift Reactors, CO Clean-up, Heat Exchangers)

<u>Power Generation Components</u>

DC/AC Inversion: A fuel cell outputs DC power which needs to be inverted to provide the 115/208 VAC, 3 phase, 400 Hz power used in most existing aircraft. Solid state inverters offer the most promising method of inverting DC power to AC. The auto makers and the Government are actively involved in inverter technology and current inverter technology exists that is capable of

supplying the power required for a fuel cell powered ground generator. Both commercial and proprietary inverter technologies were examined; however, the companies involved in proprietary inverter development would not disclose any information without a non-disclosure agreement. Table 3 provides a summary of the non-proprietary inverter technologies examined.

Type	Power (kW)	Eff (%)	Dimensions (L"xW"xH")	Volume (ft^3)	Weight (lbs)	MTBF (hours)	Unit Cost ($)
True Sine Wave	150	89	72x72x30	90	4000	45,000	$97,000
True Sine Wave Water Cooled	150	89	36x72x30	45	1330	45,000	Not Avail
Mod Sine Wave	128	95	15x21x25	5	250	45,000	$50,000

Table 3. Power Inverter Specifications

Surge Power Source: Current technology PEM fuel cells require a short duration to transition up to full power once a load is applied. The power curve is approximately 10 seconds to ramp from 10% to 90% maximum power. Several technologies were evaluated as potential solutions to provide surge power. These included batteries, fly wheel energy storage devices, and ultra capacitors. Despite their unacceptable cost in today's market, ultra capacitors appeared to be the best selection relative to weight, size, and reliability. Their cost is expected to drop significantly over the next five years to the point where they are comparable to current capacitor prices. Specifications for the ultra capacitors are provided in Table 4.

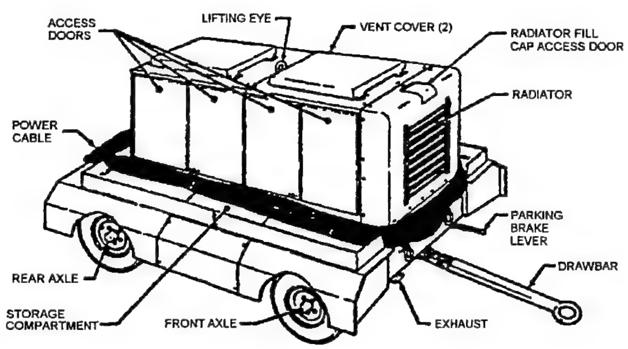
Technology	Power (kW/s)	Eff (%)	Dimensions (L"xW"xH")	Volume (ft^3)	Weight (lbs)	MTBF (hours)	Cost ($)
Current	15/10 sec	99	0.59x24x24	0.2	65	500,000	$100,000
7 Year Pred	15/10 sec	99	0.3x12x12	0.025	32.5	500,000	< $5000

Table 4. Ultra Capacitor Specifications

The seven year fuel cell prediction (see Table 1) shows the fuel cell transition time from 10% to 90% maximum power to be less than one second to reach 90% peak power. This short transition time will probably negate the need for any surge device. A secondary power system would only be necessary if supplemental power were needed to meet peak power demands.

V. COMPARISON OF FCP GENERATOR TO A/M32A-86D GENERATOR

A comparative analysis between FCP AGE and combustion engine powered AGE was performed to first determine if FCP AGE could compare favorably with current internal combustion engine AGE power-to-weight and power-to-size ratios, operation, maintainability, and ownership costs. The baseline comparison system used was the A/M32A-86D which is a widely used diesel powered ground generator cart. An illustration of the A/M32A-86D is shown in Figure 3.



72 kW @ 0.8PF, 400 Hz, 120/208VAC or 230/400V, 3-phase, 4-wire

No DC output

Max dry weight = 5730 lbs.

Volume (including cart) = 323 ft^3

Dimensions = 100"L x 78"W x 71"H

Reliability = 450 hours MTBF

Figure 3. Illustration of A/M32A-86D Ground Generator

A comparable FCP ground generator cart configuration was selected utilizing a one-for-one replacement of several diesel generator system components. Specifically, the diesel engine was replaced with a fuel cell power unit, the generator with a DC/AC inverter, and the diesel fuel delivery system with a reformer (or fuel processor to convert JP-8 to hydrogen). Table 5 identifies the unique components of the FCP generator. The remaining system components such as instrumentation, control features, cables, and the frame were assumed to be the same.

System Function	Diesel Powered Generator	FCP Generator
Primary power	Diesel engine	80 kW fuel cell stack
Surge power	Not applicable	Six 15 kW/10 sec ultra capacitors
Type of fuel	Diesel or JP-8	JP-8
Fuel source	Diesel fuel tank	JP-8 fuel tank through fuel processor (reformer)
AC power output	AC generator	Modified sine wave DC/AC inverter

Table 5. Diesel Generator and FCP Generator Primary Components

Diesel Engine & FCP Generator System Requirements

System requirements were generated to establish basic design related criteria for use in the comparative analysis. The basic criteria for the FCP generator was to provide AC power comparable to the A/M32A-86D generator and be no worse than the -86 generator in the areas of weight, size, reliability & maintainability, operational ease, and overall logistics supportability. The system requirements for both the -86 and FCP generator are outlined in Appendix C.

The maximum power requirement for the FCP generator was approximately 80 kVA for 3 phase, 120 VAC, 400 Hz power. This value was determined based on providing a total output equal to 72 kW of AC power provided by the -86 generator. Assuming an inverter efficiency of 90%, the fuel cell would have to provide approximately 80 kW of power.

System Components

The FCP generator configuration identified in Table 5 was compared with the -86 generator in the following areas:

- weight & volume
- reliability & maintainability
- life cycle cost

Footprint was not evaluated in the comparative analysis since the fuel cell and reformer modules can be dimensioned as appropriate to satisfy specific overall cart dimensions. Furthermore, the other power components which do have set dimensions could be oriented as needed to optimize the overall cart footprint.

The FCP generator comparisons were performed using both current year 1997 technology and 2004 technology levels. The year 2004 technology was included in the analysis to show the projected FCP generator's performance in the timeframe when a FCP generator would probably be initially deployed.

Weight and Sizing Estimates

Table 6 shows the estimated weight and volume of an 80 kW fuel cell. These values are based on the DOE fuel cell performance data provided in Table 1.

Year	Power Density (w/l)	Specific Power (w/kg)	Volume (liters)	Volume (ft3)	Weight (kg)	Weight (lbs)
1997	300	300	266.7	9.4	266.7	587.9
2000	350	350	228.6	8.1	228.6	503.9
2004	500	500	160.0	5.7	160.0	352.7
2008	500	500	160.0	5.7	160.0	352.7

Table 6. 80 kW Fuel Cell Stack Estimated Volume and Weight

Table 7 shows the estimated weight and volume of a reformer capable of supporting a 80 kW system. These values are based on the DOE fuel cell performance data provided in Table 2.

Year	Power Density (w/l)	Specific Power (w/kg)	Volume (liters)	Volume (ft^3)	Weight (kg)	Weight (lbs)
1997	400	400	200.0	7.1	200.0	440.9
2000	600	600	133.3	4.7	133.3	293.9
2004	750	750	106.7	3.8	106.7	235.2
2008	750	750	106.7	3.8	106.7	235.2

Table 7. Flexible Fuel Processor for an 80 kW Power Plant Estimated Volume and Weight

Table 8 summarizes the weight and volume data of the DC/AC inverter and ultra capacitor banks. The weight and volume specifications for these power generation components were provided by manufacturers. Only data for year 1997 are provided. No year 2004 data were available by the manufacturer for the inverter and the year 2004 projected fuel cell transit time to maximum power is short enough to negate the need for a supplemental power source.

Component	Weight (lbs)	Dimensions (in)	Volume (ft^3)
DC - AC Inverter	250	15x21x25	5.0
Ultra Capacitor (1)	65	0.59x24x24	0.2

Table 8. Power Generation Component Weight and Size Estimates

Reliability & Maintainability Estimates

The reliability analysis was a simple reliability prediction model using the exponential failure rate model. The reliability values for the fuel cell and reformer were taken from the DOE performance data in Tables 1 and 2, respectively. The reliability of two 40 kW fuel cell stacks were assumed to be equivalent to an 80 kW stack reliability. Vendor reliability numbers were used for the power generation components. The overall system reliability provided for the -86 generator is a specified reliability, not a computed reliability. The actual reliability is probably much higher according to the maintenance data we collected.

The maintenance analysis addressed scheduled maintenance, unscheduled maintenance, maintenance levels, and maintenance personnel required to support the current -86 generator and a FCP generator. Appendix D contains the maintenance analysis data for the -86 generator and projected maintenance data for a FCP generator. The data were collected from interviews with flight line and AGE shop technicians from the 445AW, 58ANG, 1FW, and 88ABG and compiled into the summary data contained in Appendix C.

Life Cycle Cost Analysis Estimates

A life cycle cost analysis was performed to assess the acquisition and ownership costs between the -86 generator and the FCP generator. The analysis computes the cost of a single generator unit over a 20 year period. The life cycle cost is an aggregate of the acquisition cost, operating costs (fuel costs), and maintenance costs. The methodology used to compute these costs is contained in Appendix E. Since the cost estimates are a rough order of magnitude, inflation factors and discount rates were not applied in the analysis. The assumptions used in the analysis were:

- 20 year ownership period
- Acquisition costs do not include R&D costs
- Fuel cell annual fuel costs assumed equivalent for 1997 and 2004 technology
- $0.75/gallon diesel fuel cost
- 1997 dollars
- MMH costs not computed

Results of FCP Generator and A/M32A-86D Comparative Analysis

Weight & Size

A comparison between the weight and volume of the -86 generator and the FCP generator is shown in Table 9. The FCP generator weighed less and was smaller than the current -86 generator. The weight and sizing estimates are not detailed estimates and should not be considered as

definitive values. Items such as plumbing and storage tank(s) are not included in the estimates and could add significant weight and/or volume. Even so, the FCP generator design has considerable weight and sizing margins to accommodate any required items not explicitly included in the design analysis.

Design	Weight (lbs)	Vol (ft^3)
Diesel	5,730	323
FCP (1997)	3,169	187
FCP (2004)	2,338	179

Table 9. Weight and Volume Comparison Between A/M32A-86D Generator and FCP Generator

Reliability & Maintainability

The reliability comparisons shown in Table 10 indicate that the 1997 technology level FCP generator is approximately the same as the specified reliability of the -86 generator. The poor reliability is driven by the low reliability of the fuel cell and reformer at this point in time. As the fuel cell and reformer reliability improve over time, the FCP generator reliability improves significantly as is evidenced by the reliability predictions for the year 2004 FCP generator. Assuming the DOE's projections hold true, the FCP generator would be approximately three times more reliable than the -86 generator specified reliability.

It is important to note that fuel cell reliability is defined as the number of hours the fuel cell will operate with no more than a 5% degradation in power output. In reality, the fuel cell can continue to supply power after it has reached its "failure" point. Therefore, the reliability comparison between the FCP generator and the -86 generator is somewhat misleading as the quoted MTBF assumes a hard failure. The FCP generator reliability is actually higher given the graceful degradation of the fuel cell stack.

Design	Rel (hrs)	Maint (evts/yr)	MMH (hrs/yr)
Diesel	450[1]	37.0	61.2
FCP 1997)	478	45.2	63.3
FCP (2004)	1,468	38.8	45.2

Note 1: Specified reliability. See discussion in life cycle cost paragraph for explanation.

Table 10. R&M Comparison Between A/M32A-86D Generator and FCP Generator

The maintenance analysis results in Table 10 indicate that the FCP generator in most cases actually has slightly more maintenance events per year than the -86 generator. However, the maintenance manhours for the FCP generator start to decline as the technology improves. This is expected as the FCP generator components would incorporate a more modular design and replace the support intensive complex mechanical components with more maintenance friendly solid state devices.

The majority of maintenance events and manhours stem from scheduled maintenance activities (i.e., six month and one year PE). For the purposes of the maintenance analysis, the -86 generator scheduled maintenance activity was also used for the FCP generator. In reality, we expect that the FCP generator will require significantly less scheduled maintenance. The majority of the FCP generator components would incorporate internal diagnostic routines and would typically run until failure. This will result in the FCP generator showing a significant reduction in maintenance events and manhours over the current -86 generator.

Life Cycle Cost

The life cycle cost analysis results shown in Table 11 indicate that current year 1997 fuel cell technology is too expensive and cannot compete with a diesel engine powered generator. The high cost of 1997 technology is driven by low fuel cell and fuel processor reliability and expensive equipment costs. The seven year prediction fairs much better showing the FCP generator life cycle costs dropping off significantly and being comparable to diesel powered generators. The lower life cycle costs are the result of increased fuel cell and fuel processor reliability and a significant drop in equipment costs. These improvements should be made possible through the enormous investment of the auto industry and the Government in fuel cell related technology.

Design	R&R Cost ($/yr)	Fuel Cost ($/yr)	Acq Cost ($)	LCC ($)
Diesel	$6,745	$14,062	$86,556	$502,706
FCP (1997)	$178,155	$5,400	$757,250	$4,428,350
FCP (2004)	$10,500	$5,400	$96,625	$414,625

Table 11. Life Cycle Cost Comparison Between A/M32A-86D Generator and FCP Generator

One interesting observation is that the FCP generator annual maintenance costs are more than the current -86 generator, even though the -86 generator has a worse MTBF. The -86 generator reliability or MTBF shown is a specified reliability, not an actual reliability. The maintenance collected suggests the -86 generator reliability is probably much higher. At any rate, the total annual costs (maintenance plus fuel) are less for the FCP generator.

Generator Comparison Summary

Overall, the FCP generator compared very favorably against the current A/M32A-86D generator. Considering the timeframe when a FCP generator would be initially deployed, a FCP generator would be smaller and lighter, more reliable, less maintenance intensive, and have a lower ownership cost. With the fuel cell performance and logistics feasibility issues now resolved, the study next examined some FCP generator concepts not subject to the restrictions imposed in the preceding comparative analysis.

VI. FUEL CELL POWERED AGE FOR F-22 AIRCRAFT AND BEYOND

The design comparisons made above assumed a one-for-one replacement to substitute FCP generator components for the current -86 generator components. While this approach facilitated a more direct comparison of the -86 and FCP generator technologies, it constrained the design process from taking advantage of the inherent modularity characteristics offered by the fuel cell and associated power generation components. We evaluated other design alternatives that would take advantage of the modularity features and that were not restricted to adhering to the current AGE operation and maintenance concepts. Two design concepts of special interest were explored: (1) FCP AGE using a modular DC bus architecture and (2) placing the JP-8 reformer in a centralized location.

DC Bus Modular AGE Architecture

The current AGE ground power generators use rotating internal combustion engines on a common shaft to a rotating armature AC generator. In the past, this type of generator was the only reasonable source of portable power and had the additional advantage of producing AC power compatible with existing aircraft internal AC power systems. However, for newer aircraft like the F-22 and the Joint Strike Fighter (JSF) that incorporate a DC internal aircraft power system, an extra cart must be added to convert the AC power from existing ground generator carts to DC power.

In the preceding -86 generator and FCP generator comparison, the DC output power from the FCP generator fuel cell was converted to 115V, 3 phase, 400 Hz AC power to facilitate the comparison of a DC/AC solid state inverter module to the -86 mechanical AC generator. Since the FCP generator acquisition cycle would be relatively concurrent with the acquisition of the next generation aircraft which are utilizing DC internal aircraft power, it would be reasonable to assume that FCP generator systems will provide DC power as the primary power output. A portion of the DC power would be converted to AC power only when needed to support older aircraft currently in service or to drive other equipment such as AC powered tools.

Figure 4 shows a block diagram of a modular DC bus FCP generator. This system architecture features a central DC bus in which modular devices are added to provide a specific AGE functional capability. This architecture is a variation of a DC bus system being developed for

Navy surface ships. The system is designed as a modular system to use the inherent modular features of a fuel cell power system.

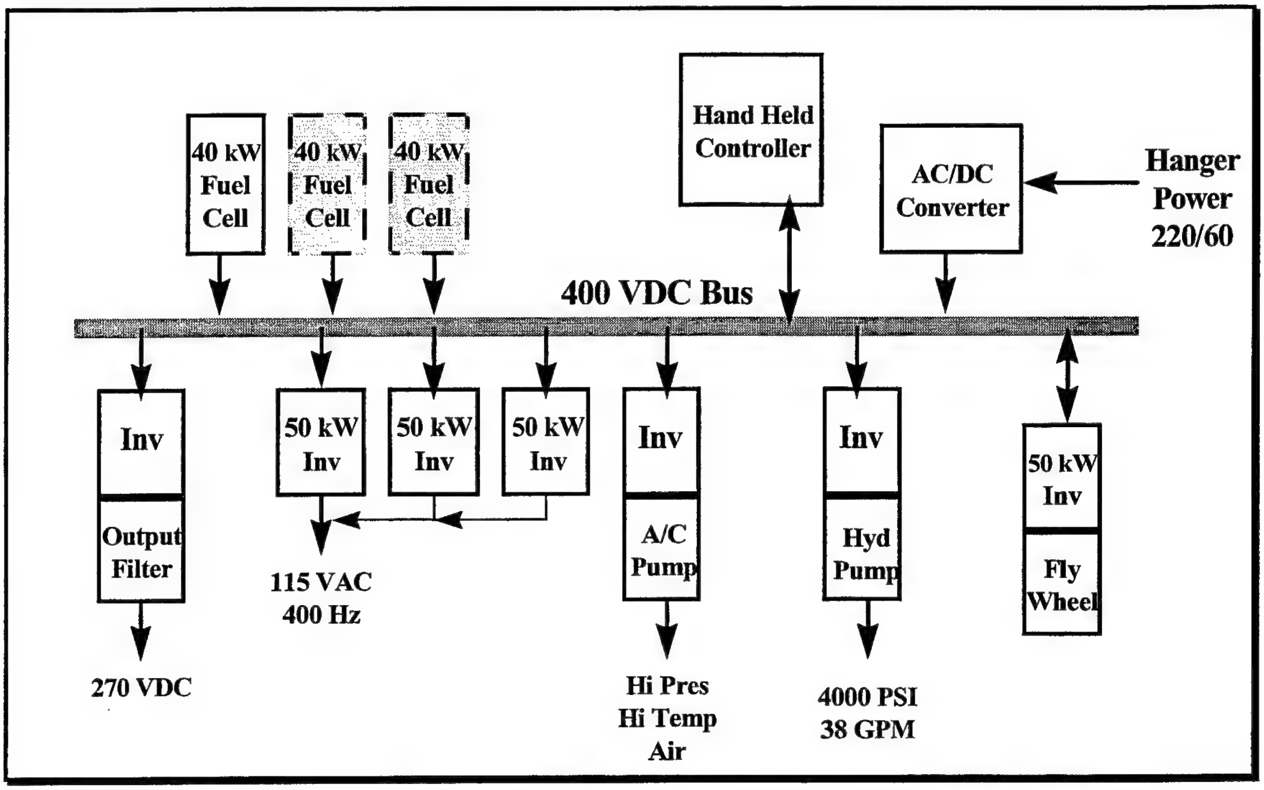


Figure 4. Modular DC Bus Architecture

System Primary Power

Fuel cell(s) are the primary power source providing the power to operate the various system modules. The number of fuel cell modules attached to the bus is determined by the power requirements. For instance, the study examined the aircraft power requirements for several tactical and airlift aircraft and found the maximum power requirement to be approximately 90 kW (see Appendix F). However, discussions with flight line technicians and AGE Shop personnel indicated that 30 kW to 40 kW is sufficient for the majority of flight line activities. These activities include preflight checks by ground personnel and aircrews and typical aircraft maintenance actions.

A 40 kW fuel cell was selected for this design concept. A fuel cell of this size, running on reformate, would weigh approximately 175 lbs. and have a volume of approximately 3 ft^3 based on the DOE projections for year 2004 fuel cell technology (1/2 the size of the fuel cell shown in Table 6). Such a fuel cell stack would be approximately 18"x18"x24". Since a fuel cell stack size can be varied without scaling costs, the size of a production fuel cell module can be optimized without compromise to satisfy all the operational, deployment, and life cycle cost issues. Since fuel cell power plants are made up of combinations of fuel cell stacks, the USAF could opt for modules of various sizes, for instance, a 20 kW module, a 40 kW module, and/or an 80 kW module.

Year	Power Density (w/l)	Specific Power (w/kg)	Volume (liters)	Volume (ft^3)	Weight (kg)	Weight (lbs)
1997	300	300	133.4	4.7	133.4	293.9
2004	500	500	80.0	2.9	80.0	176.4

Table 12. 40 kW Fuel Cell Stack Estimated Volume and Weight Running on Reformate

Other System Modules

Any number of AGE functional modules could be attached to the DC bus. The key modules are shown; a DC/DC converter to provide DC aircraft internal power to the F-22, DC/AC inverter(s) to provide AC power (the number of inverters are determined by the power level needed), and two pumps to provide hydraulic power (F-22 hydraulic power requirements shown) and to provide high pressure cooling air. The pumps portrayed in this design concept use high speed motors that are already being developed by the Navy. The size of these high speed motors is inversely proportional to the rotor speed. For example, a 30,000 rpm device would be 1/10 the size of a similar 3,000 rpm device. Other power output devices or modules in the design concept include:

- DC/AC inverter to provide single phase 115 VAC, 60 Hz power for electric tools.
- AC/DC converter module to allow the AGE unit to be plugged into a commercial power outlet for use inside a hanger.

Another modular device illustrated in Figure 4 that may be required in a FCP AGE system is an integral fly wheel and inverter. The preceding section discussed the slow response time of current generation fuel cells and identified the need to provide a supplemental power source to offset the fuel cell's power curve response. SatCon, Inc., was just awarded a contract for a similar flywheel for a missile application. They estimate that a flywheel device for this application would be approximately 12" in diameter and 15" long. Such a fly wheel system, if used in a ground cart application, would be derated to reduce the fly wheel speed 1/2 to 2/3 the burst speed and the outer material changed to steel rather than composite.

Hand Held Controller

Control of the system could be accomplished using a hand held controller interfaced with the various system components. The controller would be used to control operation of the system and to query the system for status and maintenance information. Built-in-test (BIT) capability provides automated and operator initiated fault detection and isolation. System information, maintenance reports, and maintenance procedures could be generated in real time and presented to the operator using on-cart information presentation systems. While the hand held controller would normally be mounted on the cart, it could be used, for instance, by a maintenance person from a cockpit to control the power cart and all its functions, turning each of them on and off as desired.

Centralized Reforming of Hydrogen

Use of a centralized reformer had been eliminated from consideration during previous studies based on the assumption that hydrogen gas is not an existing logistics fuel as defined by DoD Directive 4120.25. One of the study's objectives was to expand the previous work and evaluate the benefits of utilizing a centralized fuel processor. The fuel for a FCP AGE unit will be JP-8. The comparison of the diesel powered -86 generator with a drop-in replacement fuel cell power plant assumed that the fuel cell system included a JP-8 fuel processor (reformer) on the cart. However, that restriction is not necessary. The hydrogen can be generated from a centralized reformer near the flight line and the hydrogen transported to the power cart.

The advantage of having the reformer on the power cart is that the hydrogen generated is fed directly to the fuel cell and the hydrogen does not have to be handled. However, there are several disadvantages of having the reformer on the power cart that need to be considered before that decision is made. Use of a centralized reformer would:

- Reduce the weight of the fuel cell power plant on each AGE unit by approximately 200 lbs.
- Lower the operating temperature of the flight line device from approximately 250°C to 80°C.
- Eliminate the compromises necessary to make a reformer applicable for use on the flight line.
- Increase fuel cell performance by approximately 30%.
- Eliminate a module from the suite of modules needed for the flight line AGE.
- Significantly reduce the start up time for the fuel cell system.
- Reduce the response time to maximum power for the fuel cell system.

If the fuel cell power plant is fueled from a hydrogen tank, then hydrogen can be procured commercially or can be generated on the base using a reformer and hydrogen purifier system, probably located in POL. Arthur D. Little Company has designed such a system currently for the gas industry that reforms natural gas and refines the reformate to produce 99.99% pure hydrogen gas. A.D. Little estimates that a similar system reforming JP-8 and capable of producing 25,000 cubic feet of pure hydrogen (standard pressure) a day could be mounted on a skid, would be approximately 5' x 6' x 4' in size, and would cost approximately $150,000. Such a device could be deployed on one C-130 pallet.

The most compelling rationale for a centralized reformer is that reformate, which is only 50% hydrogen, reduces the power output of a fuel cell by approximately 30%. A 40kW fuel cell running on hydrogen versus reformate would be 23% smaller in weight and volume. Table 13 contrasts the reduced weight and volume of a fuel cell running on hydrogen versus the fuel cell in Table 12 running on reformate. A centralized reformer could produce 99.99% pure hydrogen gas which would then be transported in pressurized bottles to the individual FCP generator units and

attached. This concept would improve fuel efficiency, reduce the size and weight of individual FCP generators, and eliminate the HAZMAT issues relative to hydrocarbon fuels at the unit level.

Year	Power Density (w/l)	Specific Power (w/kg)	Volume (liters)	Volume (ft^3)	Weight (kg)	Weight (lbs)
1997	390	390	102.6	3.6	102.6	226.1
2004	650	650	61.5	2.2	61.5	135.7

Table 13. 40kW Fuel Cell Stack Estimated Volume and Weight Running on Hydrogen

Hydrogen Handling and Safety

Another major objective of this study was to investigate the impact of handling hydrogen on an operational Air Force base. Discussions with flight line and POL personnel revealed that the procedures currently in place for handling nitrogen, liquid oxygen (LOX), and gaseous oxygen are the same as those that would be required for handling hydrogen. These procedures include filling small containers from large supplies in the POL area (breaking bulk), transportation to the flight line, and removing and installing hydrogen tanks on the AGE equipment. Handling hydrogen was considered somewhat more hazardous than handling nitrogen, but less hazardous than handling LOX or gaseous oxygen, especially since the requirement to keep oxygen totally separated from any grease or oil would not be a requirement for hydrogen.

Hydrogen does not have any harmful physiological effects; it is non-poisonous. Hydrogen is a colorless and odorless gas which could present a potential safety concern if hydrogen gas were to leak from the AGE unit. Inhalation of the gas can lead to sleepiness and a high-pitched voice (same as inhaling helium). A danger of asphyxiation would exist in a closed room if sufficient hydrogen were released to displace oxygen to below 18%. These effects are minimized due to the rapid dispersal of hydrogen (see Table 14). This would not be a problem outdoors since hydrogen being lighter than air will naturally disperse in the atmosphere. However, if the AGE unit were being stored or used indoors and a leak occurred, the hydrogen gas could potentially accumulate and be circulated throughout the facility. While this is a concern, the risks of indoor leaks can be properly controlled through well engineered containment and safety systems, or proper safety precautions including use of hydrogen gas detectors which are commercially available.

The ignition and detonation properties of hydrogen-air mixtures are particularly important from a safety aspect. Table 14 shows a comparison of safety relevant thermo-physical and combustion properties of hydrogen compared with those of methane, propane, and gasoline. One of the main risks of many hydrocarbon gases is that they pool, and often remain unnoticed as a potential explosive hazard. Hydrogen is an order of magnitude lighter than the hydrocarbon fuels shown and its diffusion coefficient in air is more than an order of magnitude greater than the hydrocarbon gases. Consequently, hydrogen does not pool as do the hydrocarbon gases, but disperses rapidly by turbulent convection, drift, and buoyancy, thus shortening the duration of hazardous conditions. It should also be noted that hydrogen itself is not a pollutant in the air.

Prompt dispersion, however, favors the formation of gas mixtures within the wide flammability and detonation limits; the lower limit is the critical one in most applications and is comparable to that of other fuels. When an air/gas mixture does explode, the energy of explosion determines the damage or injury that occurs. Hydrogen energy of explosion is many times lower than methane, propane, or gasoline.

When compared to other flammable gases, hydrogen is less hazardous than many of the common gases we are exposed to, such as gasoline, propane, or natural gas. However, compared to JP-8 which the Air Force has chosen to replace JP-4, hydrogen is more likely to ignite. If hydrogen is "spilled" it is self dispersing, does not have to be washed down, and is not an environmental hazard. Unlike hydrocarbons, a hydrogen fire can be fought with water.

The US Army has conducted tests using M-16 rifle fire on 9,000 psi pressurized hydrogen bottles. M-16 rounds penetrated the bottle and released the hydrogen, but did not start a fire unless the round was tracer. A tracer round ignited a jet of released hydrogen, but did not result in an explosion.

CHARACTERISTIC	Hydrogen	Methane	Propane	Gasoline
Density (kg/cm^2) - It should be noted that hydrogen itself is not an air pollutant	0.084	0.65	0.42	4.4
Diffusion coefficient in air	0.61	0.16	0.12	0.05
Flammability limits in air (% H_2 in air)	4.0-75	5.3-15	2.1-9.5	1.0-7.6
Auto ignition temperature (K)	858	813	760	500-744
Flame temperature in air (K)	2318	2148	2385	2470
Detonation velocity In air (km/s)	1.48-2.15	1.4-1.64	1.85	1.4-1.7
Energy of explosion, volume-related (g TNT/m^3)	2.02	7.03	20.5	44.2

Table 14. Comparison of Hydrogen to Other Gases [Ref 5]

Maintenance personnel from the 88ABG, 445AW, 1FW, and 58ANG were surveyed regarding the use of hydrogen. Personnel surveyed included flight line crew chiefs, AGE Shop technicians, POL technicians, and ECS personnel. The responses ranged from indifference to no concern. In retrospect, the responses were not surprising given the high pressure gases and other dangerous materials already in use by the USAF. Examples include liquid and gaseous oxygen, liquid and gaseous nitrogen, and hydrazine.

A transition to fuel cell powered AGE would require a new look at the way AGE is designed and used. A fuel cell system is readily amenable to a modular AGE approach and would be much smaller and easier to handle than current AGE, especially if centralized JP-8 reforming was used. The most efficient use of fuel cell powered AGE would be accomplished when the fuel cell system is combined with the new high power DC and AC devices being developed for new

aircraft, Navy ships, and for fuel cell powered electrical vehicles in the commercial transportation market.

VII. CONCLUSIONS

The most significant conclusion reached is that fuel cells are a *feasible* alternative power source for flight line AGE. The comparative analysis indicated that a FCP generator power-to-weight and power-to-size ratio compared very favorably with the current -86 generator. The logistics supportability analysis also indicated that fuel cells presented no operational or logistical support problems. Other conclusions reached in this study were:

- Users (i.e., flight line technicians, AGE Shop personnel, ECS personnel) were generally positive towards the technology.
- Procedures currently exist to accommodate the handling, transportation, and use of hydrogen gas.
- Off-cart fuel reformer is more advantageous.
- Fuel cells permanently eliminate the AGE hazardous emissions problem.
- A fuel cell's silent operation reduces environmental noise and improves communication and awareness.
- Actual fuel cell power output requirements can probably be scaled down as most technicians stated the current 60 kW (-60 generator) and 72 kW (-86 generator) power output was overkill.
- Fuel cells and associated power generation technologies stimulate out-of-the-box thinking regarding AGE concepts of operation and maintenance.
- Fuel cell technology is well positioned as a practical and cost effective power source due to enormous investment by auto industry and the Government.
- Environmental regulation and limited acquisition dollars will require revolutionary versus evolutionary changes in AGE design.

VIII. RECOMMENDATIONS

Given that the fuel cell powered AGE concept appears feasible and reasonable, the logical next step is to develop a small scale prototype FCP generator to validate the specific application of this technology to AGE. The prototype would also provide a psychological benefit in that most people, while acknowledging the existence and use of fuel cells, do not have any direct association with fuel cells. A prototype unit would provide a tangible confirmation of the fuel cell's practicality and capabilities. Several prototype development concepts could be pursued. Two are listed here to stimulate thinking on how fuel cells can be used in AGE applications.

Basic AC Power Cart

This prototype concept would consist of a fuel cell and DC/AC inverter to provide a single phase 115 VAC power output. This concept would simply demonstrate that a fuel cell is a feasible power source and that an inverter can supply the required AC output power. A variation on this concept could include the addition of a reformer to demonstrate the capability to operate the cart using a diesel or JP-8 fuel source. Another variation could include multiple fuel cell modules to demonstrate the ability to stack fuel cell modules together to size a particular power requirement.

Basic DC Power Cart

New aircraft acquisitions indicate a change from the 115 VAC, 3 phase, 400 Hz, aircraft internal power to high voltage DC aircraft internal power as in the case of the F-22 and JSF. A prototype DC generator could be developed to demonstrate the ability to support DC powered aircraft using a single DC generator cart. The prototype model could include other features such as the addition of a reformer or the use of multiple fuel cell modules.

The two prototype concepts described above represent the basic features that should be demonstrated. As noted, there are many variations one could add to demonstrate additional technologies and concepts. These of course are dictated by funding, schedule, and equipment availability.

LIST OF ABBREVIATIONS

ABG	Air Base Group
AGE	Aerospace Ground Equipment
ANG	Air National Guard
AW	Airlift Wing
BIT	Built-in-test
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DoD	Department of Defense
DOE	Department of Energy
DOT	Department of Transportation
ECS	Environmental Control Section
FCP	Fuel Cell Powered
FW	Fighter Wing
HAP	Hazardous Air Pollutants
HAZMAT	Hazardous Materials
HPAP	High Pressure Ambient Pressure
H_2S	Hydrogen Sulfide
NH_3	Ammonia
JSF	Joint Strike Fighter
LOX	Liquid Oxygen
LTRS	Logistics Technology Research Support
MMH	Maintenance Manhour
MNS	Mission Need Statement
MTBF	Mean Time Between Failure
NASA	National Aeronautics and Space Administration
NMHC	Non-methane Hydrocarbons
NOX	Nitric Oxide
NTD	Non-thermal Discharge
O&M	Operation & Maintenance
PE	Periodic Evaluation
PEM	Proton Exchange Membrane
PF	Power Factor
PHS&T	Packaging, Handling, Shipping, & Transportation
PM	Particulate Matter
POL	Petroleum, Oil, Lubrication
R&D	Research & Development
R&M	Reliability & Maintainability
R&R	Repair & Replace
SE	Support Equipment
SEE-IT	Support Equipment Evaluation and Improvement Techniques
SO_2	Sulfur Dioxide
TNT	Trinitrotoluene
US	United States
USAF	United States Air Force

LIST OF SCIENTIFIC UNITS

AC	Alternating current
amp	Amperes
C*	Concentration of oxygen in bathing solution
cm	Centimeter
D	Effective diffusion coefficient for oxygen
dB	Decibel
DC	Direct current
e	Electron
ft	Foot
g	Grams
gal	Gallons
gph	Gallons per hour
h	Hours
H	Height
H_2O	Water
H_2O_2	Hydrogen Peroxide
hp	Horsepower
Hz	Hertz
J	Joules
K	Kelvin
kg	Kilogram
km	Kilometer
kVA	Kilovolt amps
kW	Kilowatt
L	Length
lbs	Pounds
m	Meter
mA	Milliamps
mBTU	Millions of British Thermal Units
mg	Milligrams
min	Minutes
O_2	Oxygen
mV	Millivolt
ppm	Parts per million
psi	Pounds per square inch
rms	Root mean square
rpm	Revolutions per minute
sec	Seconds
V	Volts
VAC	Volts alternating current
VDC	Volts direct current
W	Width
ϕ	Phase

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APPENDIX A
Fuel Cell Technology and Performance Considerations

The fuel cell is an electrochemical device that converts chemical directly into usable electrical energy without combustion as an intermediate step. Fuel cells are similar to batteries in that both produce a DC current by using an electrochemical process. Like batteries, fuel cells are combined into groups, called stacks, to obtain a usable voltage and power output. Since a fuel cell generates electricity without going through a heat generation phase, a fuel cell power plant does not have the Carnot limitation inherent in an internal combustion engine and can be scaled to the desired size with only a small loss in efficiency.

In a fuel cell, two electrodes, an anode and a cathode, are separated by an electrolyte. The electrical reaction combines hydrogen (the fuel) and oxygen (from air) to form water and release electrons that can be gathered to produce a current. The hydrogen fuel can be provided as a pure hydrogen gas or as the output of a hydrocarbon fuel processor. There are different types of fuel cells characterized by the type of electrode used. For instance, Phosphoric Acid Fuel Cells (PAFCs), Molten Carbonate Fuel Cells (MCFCs), and Solid Oxide Fuel Cells (SOFCs) are all high temperature fuel cells and are being targeted for the power industry for stationary power generation.

For smaller, mobile power requirements where rapid start up and lower temperatures are required, such as for cars, buses, or application to AGE, a Proton Exchange Membrane (PEM) Fuel Cell is normally considered.

The functional portion of a PEM Fuel Cell is the Membrane Electronic Assembly (MEA) composed of the proton exchange membrane along with the anode and cathode, illustrated in Figure A-1. When hydrogen is present at the anode, protons migrate through the PEM, leaving electrons at the anode. The protons combine with oxygen at the cathode (in the presence of a catalyst) forming water. The potential created between the anode and the cathode can be used as a direct current power source.

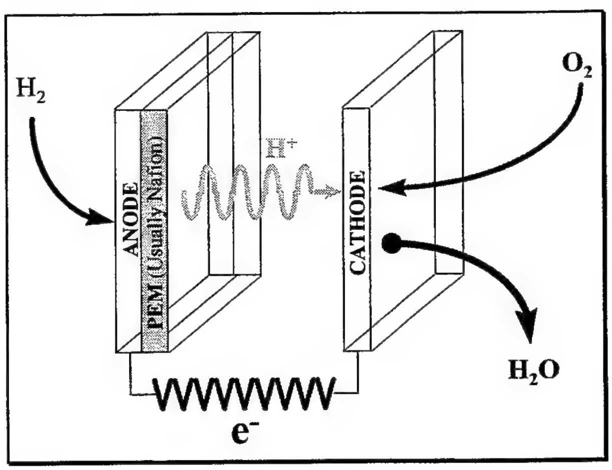

Figure A-1. Fuel Cell Membrane Assembly

Fuel cell performance is primarily determined by the efficiency of the electrochemical process at the MEA and is measured in amperes per area of membrane at a given voltage (A/cm^2). While the voltage across a given cell is relatively fixed, the amount of current generated by the cell is dependent upon the surface area (cm^2) of the PEM where the reaction can occur. The basic measure of fuel cell performance is the efficiency of the electrochemical process at the MEA and is measured in amperes per area of membrane at a given voltage (A/cm^2). Fig-

ure A-2 shows a typical fuel cell "polarization curve." The vertical axis is the voltage across the fuel cell and the horizontal axis is the current being generated per area of membrane (A/cm^2).

In the fuel cell illustrated in Figure A-2, the open circuit potential is 1 volt. When current begins to flow, there is an initial rapid drop in the voltage until approximately 300 mA due to a phenomenon called activation overpotential. From approximately 300 mA to 1300 mA, the voltage drop is constant in relation to the increasing current due to internal impedance in the fuel cell. Beyond approximately 1300 mA, there is again a rapid drop off in voltage, this time due to the inability to deliver reactants to the reaction surfaces at a rate sufficient to keep up with the current demand. A fuel cell is normally operated in the middle or ohmeric range. For the fuel cell characterized by the polarization curve in Figure A-2, the optimum operating point would be at approximately 0.7 volts and 500 mA/cm^2,or 0.35 $watts/cm^2$. A high performance PEM Fuel Cell today will operate at 1 $watt/cm^2$.

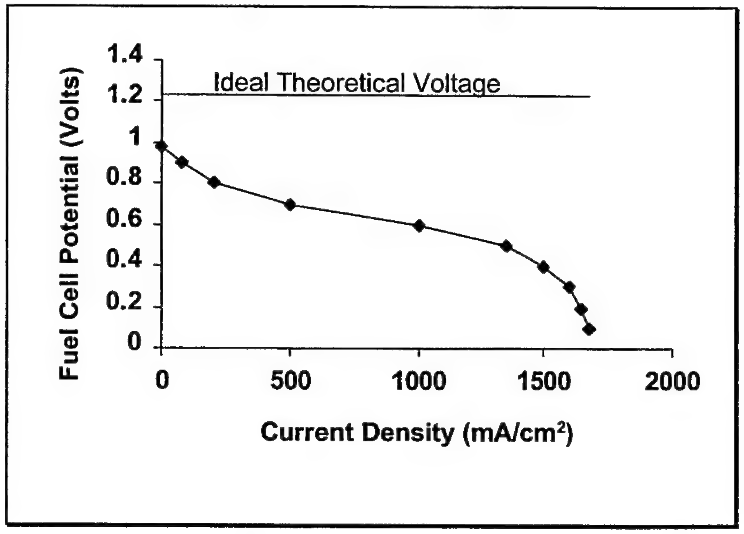

Figure A-2. Fuel Cell Polarization Curve

In order to have sufficient surface area of the PEM in a reasonable package, individual fuel cells are aggregated into a "fuel cell stack" to become a workable, refuelable power source. The cells in a stack are normally connected in series to form a basic fuel cell stack. The stacks can be further connected in series or parallel to provide a power source with the needed power output and with the desired combination of voltage and current. The total current that would be delivered by a fuel cell stack using the membrane characterized in Figure A-2 would be 500 mA times the total cross section area of the membranes in the cells making up the fuel cell stack.

There are a number of considerations in determining the performance of a fuel cell power source, but the basic issue is what will be the size and weight of the power plant that will deliver the required power. Since a fuel cell stack can easily be scaled to the needed power requirement, fuel cell performance is expressed as a ratio of the power produced (watts) per volume or weight. The two basic fuel cell performance measures that address volume and weight are:

- Power Density – the power produced per unit of volume (watts/liter - w/l)
- Specific Power – the power produced per unit of weight (watts/kilogram - w/kg)

Efficiency of the MEA is the primary factor in fuel cell performance. However, a number of external factors have significant influence on the performance of a specific MEA. These key factors are:

- Source of hydrogen fuel - pure hydrogen or output of a hydrocarbon fuel processor
- Source of oxygen - pure oxygen or air
- Catalyst Loading
- Operating Pressure

Hydrogen Source

In a fuel cell, hydrogen is delivered to the anode side of the PEM. The PEM allows the hydrogen nucleus, a proton, to migrate through the membrane to the cathode, leaving the electrons at the anode. The rate of delivery of protons to the cathode is effected by the efficiency of the membrane and by the concentration of hydrogen at the anode. A comparison of fuel cells supplied with pure hydrogen or with the direct output of reforming a hydrocarbon fuel (reformate) is shown below. The amount of hydrogen in reformat is approximately 50% due to dilution of the hydrogen by various other gases. Performance of fuel cells for fuel cells is reduced by approximately 30% when reformate is used.

<u>Current Performance</u>

Hydrogen/air cells (at 0.7 volts and 90^0C)	600-700 mW/cm2
Reformate/Air cells (at 0.7 volts and 90^0C)	500mW/cm2

<u>Year 2000</u>

Hydrogen/air cells (at 0.7 volts and 90^0C)	1000 mW/cm2
Reformate/air cells (at 0.7 volts and 90^0C)	700mW/cm2

Oxygen Supply

The number of oxygen ions at the reaction surface in the cathode available to react with the protons is dependent upon the partial pressure of oxygen at the cathode. The partial pressure of oxygen can be increased by increasing the percentage of oxygen in the gas flow to the cathode (pure oxygen versus oxygen in air) and/or by pressurizing the cathode side of the fuel cell. Figure A-3 shows the polarization curves for fuel cells operating with oxygen or air with five atmospheres of pressure or at ambient pressure.

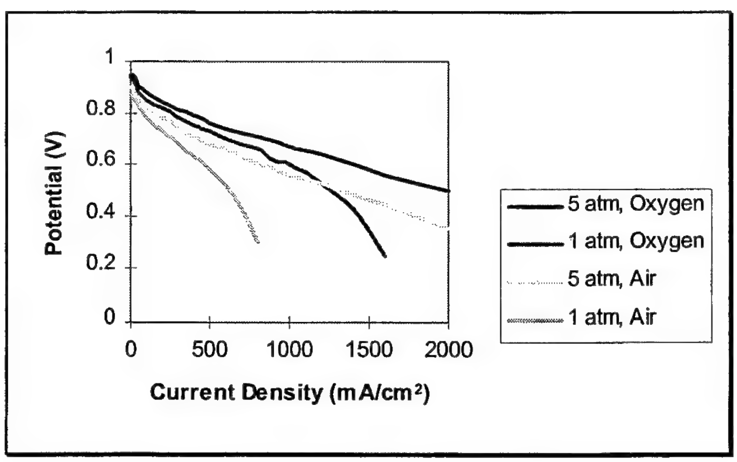

Figure A-3. Dow Membrane, 50°C

Catalyst Loading

PEM Fuel Cells normally operate at a relatively low temperature, 80-90°C. At this temperature, the electrochemical reaction in the fuel cell is slow enough that a catalyst, normally platinum, must be present for the reaction to proceed efficiently. Increasing the platinum loading will increase the rate of reaction and the power produced by the fuel cell; however, the cost of the platinum catalyst can become a major part of the total fuel cell cost.

The catalyst load that is appropriate is determined by the criticality of size and weight of the fuel cell power plant versus cost. For instance, the cost of the fuel cell "engine" in a fuel cell powered passenger car is the critical issue for success of electrical powered cars. A significant amount of research and development work is being funded by the Department of Energy to find new, less expensive catalysts or other fuel cell improvements that reduce the required catalyst content for the millions of cars expected to be powered by fuel cells.

While cost is an important factor for a fuel cell power plant for AGE, the USAF might be willing to bear some increased cost of a higher platinum load to get a significantly lower size and weight. The amount of catalyst to be used in a production USAF ground power fuel cell would be a matter of optimizing the benefits of performance in size and weight versus the increased fuel cell cost due to platinum level.

APPENDIX B
High Performance Ambient Pressure Proton Exchange Membrane Fuel Cell

The High Performance Ambient Pressure (HPAP) PEM Fuel Cell is based on a technology that uses a composite MEA to improve oxygen reduction kinetics and mass transport of oxygen at the electrode surface. Preliminary testing shows an increase in PEM fuel cell performance of up to 135%.

<u>Background</u>

A PEM Fuel Cell is an electrochemical device that combines hydrogen at an anode and oxygen from air across an electrolyte to generate electricity, producing water as a by-product. The electrodes are typically modified with a noble metal catalyst. The hydrogen and oxygen are separated from each other by a proton exchange membrane as the electrolyte to prevent thermal decomposition of the fuels in the presence of the noble metal catalyst.

The fuel cell is typically run under non-equilibrium conditions, and, as such, is subject to kinetic limitations. These limitations are usually associated with the reaction at the cathode.

$$\text{Cathode: } O_2 + 4H^+ + 4e^- = 2H_20 \qquad E^\circ{}_{cathode} = 1.23V$$

As the reaction at the cathode becomes increasingly kinetically-limited, the cell voltage drops, and a second reaction path, the two electron/two proton reduction of oxygen to peroxide, becomes increasingly favored. This consumes oxygen in a two electron step with lower thermodynamic potential.

$$\text{Cathode: } O_2 + 2H^+ + 2e^- = H_20_2 \qquad E^\circ{}_{H2O2} = 0.68V$$

The standard free energy of this reaction is 30% of the free energy available from the four electron reduction of oxygen to water. The decrease in current associated with the decreased number of electrons transferred and the decreased cell potential couple to yield substantially lower fuel cell power output.

One approach to enhance the efficiency of the cathodic reaction is to increase the concentration (pressure) of the feeds to the cathode--protons and oxygen - so as to enhance the *flux* (i.e., the reaction rate at the cathode in moles/cm^2) at the cathode. The proton flux is readily maintained at a sufficiently high value by the proton exchange membrane so as to meet the demand set by the cathodic reaction. Normally, the method of enhancing the flux and biasing the reaction to favor the formation of water is to pressurize the air feed to the cathode. Pressures of 5-10 atmospheres are typical.

Pressurization of the cathode requires mechanical compressors using parasitic power from the fuel cell. The result is approximately 15% reduction in the power output of the total

fuel cell system, limitation in fuel cell packaging options, and addition of a mechanical device to a solid state system.

<u>High Performance Ambient Pressure PEM Fuel Cell</u>

HPAP PEM Fuel Cell development is based on the use of a composite material local to the reaction surface of the electrode that improves both flux and kinetics. The incorporation of this composite in the MEA has been tested with cyclic voltammetry and is currently being tested in fuel cells.

The results of the cyclic voltammetry is presented in Figure B-1. The value $kD^{1/2}C^*$ is plotted versus the volume percentage of platinized carbon in film. The peak current determined as a function of cyclic voltammetric scan rate yield $kD^{1/2}C^*$, is essentially a measure of flux. The parameter, $kD^{1/2}C^*$, is set by D, the effective diffusion coefficient for the oxygen into the film, and C* is the concentration of oxygen in the bathing solution. Concentration of oxygen in solution is measured by an oxygen sensor and is approximately 28 mg/liter. The error bars on each plot are one standard deviation for multiple replicates of each point.

As shown at Figure B-1, integration of the HPAP composite material into current fuel cell MEA material has demonstrated as much as a 12 fold enhancement in oxygen flux. This enhancement is the equivalent of increasing the partial pressure of oxygen in ambient pressure air to 12 atmospheres, twice the normal pressurization of fuel cells. Such an enhancement will remove the pressurization requirement from the HPAP PEM Fuel Cell to allow efficient design of a modular fuel cell minimizing the volume and weight of the fuel cell power system.

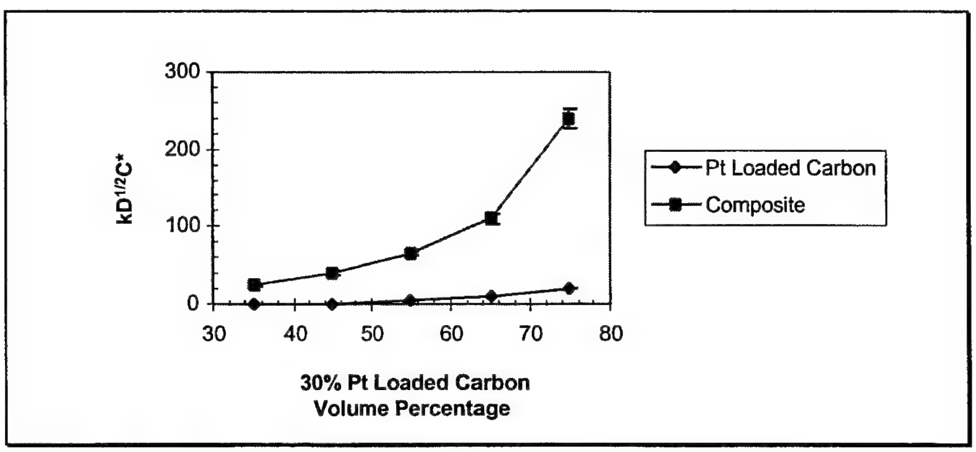

Figure B-1. Oxygen Flux Enhancement Resulting from Integration of HPAP Composite Material into the MEA

Beyond the flux enhancement associated with the HPAP PEM Fuel Cell technology, the composite MEA has also shown a positive potential shift for oxygen reduction kinetics. While the size of this potential shift has not been extensively quantified in fuel cell operation, a minimum positive potential shift of 35 mV should be seen and a potential shift of +100 mV is anticipated. For a fuel cell operating at 500 mA/cm^2 and 0.7V, a +35 mV potential shift is a 5% increase in voltage and a +100 mV shift is a 10% increase in voltage. The potential shift allows for operation at higher current density, resulting in a 35% and 100% increase respectively in power output of the fuel cell (Figure B-2).

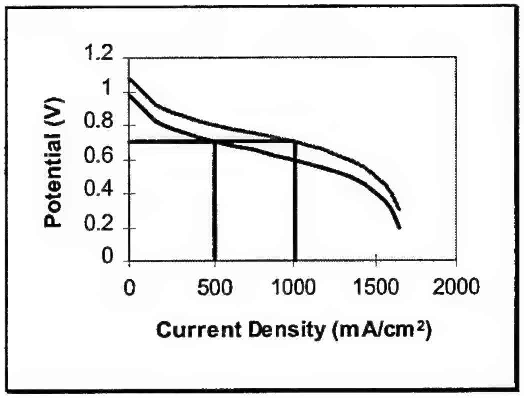

Figure B-1. Potential Shift for Oxygen Reduction Kinetics Based on Integrating the HPAP Composite Material into the MEA

Again, considering a fuel cell operating at 500 mA/cm^2 and 0.7V, the potential shift combined with the removal of the pressurization pumps (and the parasitic power loss of 15%) show dramatic increases in fuel cell power output. The minimum +35 mV shift will result in a total increase of 59% in fuel cell power output, and the anticipated +100 mV shift will result in a 135% increase in fuel cell system power output.

An attractive feature of the HPAP PEM Fuel Cell technology is that the increases in fuel cell performance are additive to other fuel cell advances. For instance, the Department of Energy is funding developments in catalyst technologies to reduce both the amount of catalyst and its cost. There are also developments in electrode efficiencies. Both of these technologies, along with other advances, can combine with HPAP to provide the 2-3 times improvement in fuel cell performance believed necessary for wide spread commercial use of fuel cells.

APPENDIX C
A/M32A-86D and FCP Generator System Requirements

SPECIFICATION	A/M32A-86	SOURCE	FUEL CELL CART	SOURCE
AC Power Output, nominal	72 kVA	T.O. 35C2-3-469-11	60 kVA	SEE-IT Database
AC Power Output, max	90 kVA	nom + 25%, (Note[1])	90 kVA	SEE-IT Database
AC Power Output, surge	90 kVA	nom + 25%, (Note[1])	90 kVA	SEE-IT Database
AC System Voltage	113-118 VAC	MIL-STD-704E	3.0V, rms max	MIL-STD-704E
AC Voltage Unbalance	3.0 V, rms max	MIL-STD-704E	3.0V, rms max	MIL-STD-704E
AC Voltage Modulation	2.5 V, rms max	MIL-STD-704E	2.5V, rms max	MIL-STD-704E
AC Voltage Phase Diff	116° - 124°	MIL-STD-704E	116° - 124°	MIL-STD-704E
AC Distortion Factor	0.05 maximum	MIL-STD-704E	0.05 maximum	MIL-STD-704E
AC Steady State Frequency	393 - 407 Hz	MIL-STD-704E	393 - 407 Hz	MIL-STD-704E
AC Peak Voltage	271.8 V, rms max	MIL-STD-704E	271.8 V, rms max	MIL-STD-704E
DC Power Output, nominal	N/A	N/A	70 kVA	SEE-IT Database
DC Power Output, max	N/A	N/A	70 kVA	SEE-IT Database
DC Power Output, surge	N/A	N/A	87.5 kVA	SEE-IT Database
DC System Voltage	N/A	N/A	260V - 280V	MIL-STD-704E
DC Distortation Factor	N/A	N/A	0.015 max	MIL-STD-704E
DC Ripple Amplitude	N/A	N/A	6.0V max	MIL-STD-704E
DC Transient Voltage	N/A	N/A	Note[1]	MIL-STD-704E
Max Weight, Dry (w/cart)	5730 lbs.	T.O. 35C2-3-469-11	5730 lbs.	T.O. 35C2-3-469-11
Max Dimensions (w/cart)	100"L x 78"W x 71"H	T.O. 35C2-3-469-11	100"L x 78"W x 71"H	T.O. 35C2-3-469-11
Max Cubage (w/cart)	323 ft^3	T.O. 35C2-3-469-11	323 ft^3	T.O. 35C2-3-469-11
Reliability (MTBF)	450 hours	Specified	2000 hours	Specified
Operating Temperature Range	-25 to 125 °F	T.O. 35C2-3-469-11	-25 to 125 °F	T.O. 35C2-3-469-11

Table C-1. Generator System Requirements

Note 1: Normal voltage transient for 270 VDC system is provided in Figure 10, page 22 of MIL-STD-704E [Ref 3].

APPENDIX D
Operation and Maintenance Analysis Data

Operation and maintenance data for the A/M32A-86D generator were collected from the 445AW AGE Shop. The -86 generator operation profile is listed in Table D-1 and the related maintenance data are found in Table D-2.

PERFORMANCE SPEC	PARAMETER VALUE/DESCRIPTION
Fuel Tank Capacity	50 gallons
Hours Run on a Full Tank	16-17 hours/tank
Hours Run per Day	18-20 hours/day
Hours Under Load	6 hours/day
Cold Temperature Characteristics	Needs ether charger; AGE Shop starts and warms up to provide improved governor response
Hot Temperature Characteristics	Performs great in hot and dry temperature
Humidity Characteristics	Heavy rain and high humidity cause solid state electronic failures; normal repair is to dry out

Table D-1. A/M32A-86D Operation Profile

MAINTENANCE TYPE	MAINTENANCE ACTION	MAINTENANCE RATE	ITEM COST	MANHOURS
Scheduled	Minor PE	180 days	$100	3-8, 4 avg
	Major PE	1 year	$500	12-24 hours
Unscheduled	Tweaking	125 hours	N/A	1
	Replace/repair circuit cards	No data	No data	No data
	Replace governors	26,000 hours	$7000	32
	Replace voltage regulators	No data	No data	No data
	Replace electronic governor	19,000 hours	$300	4
	Replace mechanical governor	26,000	$360	4
	Replace engine	10,000	$12,000	

Table D-2. A/M32A-86D Maintenance Profile

A maintenance analysis was performed for the -86 generator and an equivalent FCP generator. The data used in this analysis are contained in Tables D-3 through D-5. The assumptions used in the analysis were:

- 4,500 operating hours per year for both -86 and fuel cell generator,
- Replacement spares do not include PHS&T costs,
- MMH costs were not computed,
- Fuel cell failure is defined as 5% power loss, and
- Reformer failure is defined as a catalyst replacement.

-86 Generator	MTBF	Events/yr	MMH/event	Annual MMH	Unit Cost	Annual R&R Cost
Engine	10,000	0.4500	40	18.0000	$12,000	$5,400
Generator	26,000	0.1731	32	5.5385	$7,000	$1,212
Elect Gov	19,000	0.2368	4	0.9474	$300	$71
Mech Gov	26,000	0.1731	4	0.6923	$360	$62
Adjust/Calibration	125	36.0000	1	36.0000	$0	$0
Total	450(1)	37.0330		61.1781		$6,745

Table D-3. A/M32A-86D Generator Maintenance Data

FCP Generator (1997)	MTBF	Events/yr	MMH/event	Annual MMH	Unit Cost	Annual R&R Cost
Fuel Cell	1,000	4.50000	4	18.0000	$25,000	$112,500
Reformer	1,000	4.50000	2	9.0000	$6,250	$28,125
Ultra Capacitor	83,000	0.0542	2	0.1084	$600,000	$32,530
Inverter	45,000	0.1000	2	0.2000	$50,000	$5,000
Adjust/Calibration	125	36.0000	1	36.0000	$0	$0
Total	478(2)	45.1542		63.3084		$178,155

Table D-4. FCP Generator Maintenance Data Projections (1997 Technology)

FCP Generator (2004)	MTBF	Events/yr	MMH/event	Annual MMH	Unit Cost	Annual R&R Cost
Fuel Cell	2,500	1.8000	4	7.2000	$4,375	$7,875
Reformer	5,000	0.9000	2	1.8000	$1,250	$1,125
Inverter	45,000	0.1000	2	0.2000	$15,000	$1,500
Adj/Cal	125	36.0000	1	36.0000	$0	$0
Total	1,468(2)	38,8000		45.2000		$10,500

Table D-5. FCP Generator Maintenance Data Projections (2004 Technology)

Note(1): Specified reliability of 450 hours.
Note(2): Includes 1700 hour MTBF for structural, plumbing, and other components.

APPENDIX E
Life Cycle Cost Analysis Methodology

Maintenance Costs

The maintenance analysis focused on repair and replacement (R&R) costs and maintenance manhours (MMH) for unscheduled maintenance activities. Scheduled maintenance activities such as minor and major PE were considered equivalent and were not accounted for in the comparative analysis. The analysis results are tabulated for a one year comparison between a single -86 comparable diesel powered generator and a fuel cell generator.

Data for the current -86 generator were provided by the 445AW AGE Shop. Reliability data for the fuel cell powered generator were estimated using manufacturer provided quotes and the fuel cell and fuel processor technical targets provided in Tables 1 and 2, respectively. The maintenance parameter values and calculations are contained in Appendix D.

Fuel Operating Costs

Fuel operating costs were computed using the utilization rates shown in Table E-1. Battelle's EMAGE Report [Ref 1] published an estimated annual fuel consumption for a 100 kW fuel cell generator. These fuel consumption rates were scaled for an 80 kW fuel cell under 25%, 50%, and 100% loading conditions. An equivalent diesel engine powered generator fuel consumption rate was taken from data provided by the 445 AW AGE Shop.

Power Source	Load Condition	Fuel Rate (gph)	Duration (hrs)	Fuel Usage (gal)
Diesel Engine	Aggregate Load	3.125	4,500	14,062.50
Fuel Cell	0%	0.400	3,000	1,200.00
	25%	1.200	500	600.00
	50%	2.400	500	1,200.00
	100%	4.800	500	2,400.00
		Total --	4,500	5,400.00

Table E-1. Annual Fuel Consumption Profile

The basic operation concept for the FCP generator was compared against the -86 generator using the same operating profile. For this analysis, a generator runs 18-20 hours per day with the generator under load for approximately a third of that time, 6 hours. Table D-1 contains the operating profile used in the analysis. Data from the 445 AW indicate the -86 consumes an average of 3.125 gallons of fuel per hour over the normal day. Assumptions used in the analysis were:

- Operate 18 hours per day, 5 days per week, 50 weeks per year.
- Six hours per day under load.